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Deriving cloud overlap statistics from radar

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ABSTRACT

The predictions of General Circulation Models (GCMs) are sensitive to the assumed cloud overlap within a vertical column of model gridboxes, but until now no reliable observations of the degree of cloud overlap have been available. In this note we derive the overlap characteristics of clouds from 71 days of high vertical resolution 94-GHz cloud radar data in the UK. It is found that, contrary to the assumption made in most models, vertically continuous clouds tend not to be maximally overlapped. Rather, the overlap of clouds at two levels tends to fall rapidly as their vertical separation is increased, and for levels more than 4 km apart, overlap is essentially random. A simple inverse-exponential expression for the degree of overlap as a function of level separation is proposed that could, once results become available from a variety of other locations and seasons, be implemented in current GCMs with relatively little difficulty.

1. Introduction

The distribution of clouds in the atmosphere represents one of the major uncertainties in our understanding of the present climate (IPCC 1995), and limits our confidence in future climate prediction. General Circulation Models (GCMs) currently carry a value for cloud fraction in each model gridbox but it has been found that different assumptions on the way clouds overlap in a vertical column of gridboxes can have a strong effect on the model radiation budget (Morcrette and Fouquart 1986; Charnock et al. 1994; Liang and Wang 1997; Stubenrauch et al. 1997). This in turn affects circulation patterns (Liou and Zheng 1984; Slingo and Slingo 1988; Randall et al. 1989). The three different cloud overlap assumptions that have commonly been made in GCMs are shown schematically in Fig. 1. Integrations of the European Centre for Medium-Range Weather Forecasts (ECMWF) model by Morcrette and Jakob (2000) highlighted the important differences between them: simulated global-mean cloud cover was 71.4% when random overlap was assumed but only 60.9% in the case of maximum overlap, and over parts of the ITCZ the resulting differences in mean outgoing longwave radiation were in excess of 40 W m^{-2}. While the importance of cloud overlap for radiation has long been recognised, it is only recently that its role in determining the efficiency of precipitation formation has also been studied (Jakob and Klein 1999).

Nearly all GCMs now employ the so-called 'maximum-random' overlap assumption, whereby vertically continuous clouds are assumed to be maximally overlapped while clouds at different heights that are separated by an entirely cloud-free model level are randomly overlapped (Geleyn and Hollingsworth 1979). The passive observational data used to support this approach has so far been very limited in vertical resolution (Tian and Curry 1989). Barker et al. (1999) carried out Monte Carlo simulations of solar fluxes on convective clouds generated with a cloud-resolving model, and found that the overlap of the model clouds differed from the generally-assumed maximum-random overlap, resulting in shortwave flux differences of up to 100 W m^{-2}. They looked forward to a time when overlap could be validated from ground-based and spaceborne radars. In this note we report new results on cloud overlap derived using high vertical resolution millimetre-wave radar. The potential of such instruments for the validation of model cloud fields was demonstrated by Mace et al. (1998) and Hogan et al. (2001).

2. Method

We use the near-continuous observations taken between 6 November 1998 and 24 January 1999 by the ESTEC 94-GHz 'Galileo' radar at Chilbolton, England. This dataset was used by Hogan et al. (2001) to derive cloud fraction for comparison with the values held in the ECMWF model. The radar was vertically-pointing and recorded radar reflectivity factor (Z) as a 10-s average with a vertical resolution of 60 m. A 6.9 dB increase in sensitivity was achieved by averaging over 2 mins and 120 m, resulting in minimum-detectable Z of around -52.5 dBZ at 1 km and -32.5 dBZ at 10 km. The clouds most likely to be undetected by radar are high thin cirrus, but it was shown by Brown et al. (1995) that virtually all 'radiatively-significant' cirrus (essentially that which decreases outgoing longwave radiation by at least 10 W m^{-2}) should be detected by a radar with a minimum-detectable Z of -30 dBZ. A reduction in the sensitivity of the instrument by 5 dB is found to have a negligible effect on the final results, so there is no reason to suppose that very tenuous clouds should have significantly different overlap characteristics from detectable clouds. Nonetheless, we restrict our analysis to data recorded below 10.5 km. Data below 750 m are not used because here the radar sensitivity is somewhat compromised by leakage of the transmit pulse into the receiver. It should be noted that the common problem of data contamination by insects is entirely absent at the latitude of Chilbolton during

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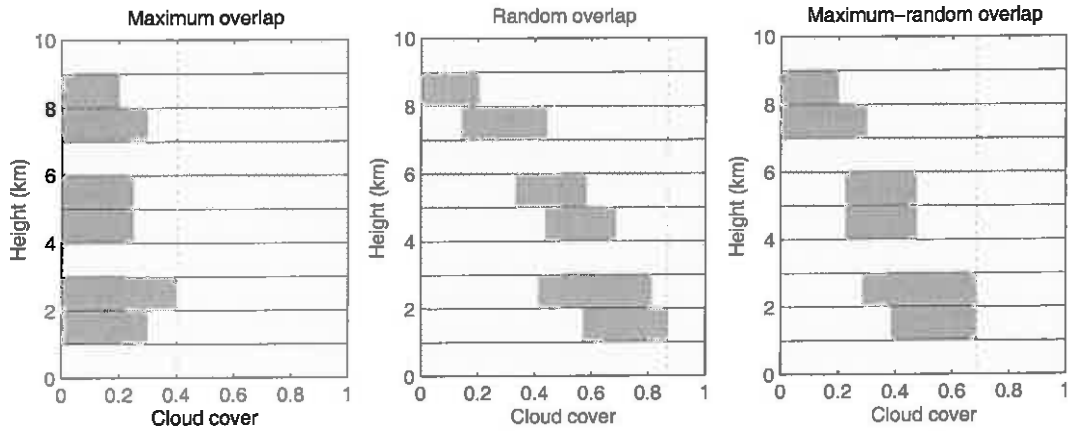

FIG. 1: A schematic illustrating the three overlap assumptions that are commonly made in GCMs. The dotted vertical lines denote total cloud cover. For clarity we have adopted the convention used by Morcrette and Jakob (2000) and drawn only a single cloud at each level. While the total cloud cover from the top of the atmosphere down to any particular level is correct, the use of a single cloud at each level in the diagram is a simplification for the overlap of any two individual layers in the cases of random and maximum-random overlap.

winter.

To compute actual overlap, daily time-height sections of Z were divided into equally-sized boxes, and within each box a simple 'cloud cover mask' was generated consisting of 'bits' stating whether or not cloud was present at any height within the box in each 2-minute period. To mimic the range of vertical and horizontal resolutions of current GCMs, box sizes of 360 m, 720 m, 1080 m and 1440 m in the vertical and 20 mins, 1 hour and 3 hours in time were used. Taking the mean tropospheric horizontal wind speed to be 20 m s^{-1} (estimated from ECMWF model data over Chilbolton during the experimental period), these temporal resolutions translate to horizontal distances of 24 km, 72 km and 216 km respectively, spanning the range of horizontal resolutions used by operation mesoscale models to climate models. Cloud cover (c) was then defined as the fraction of bits in each box that were cloudy. An example of the generation of the cloud cover mask from a 12-hour time-height section of Z is shown in Fig. 2. It might initially appear that a vertical column of gridboxes with 100% cloud cover at every level is indicative of maximum overlap, but in fact nothing can be inferred about overlap when one or more of the levels under consideration is completely cloudy, since all overlap assumptions must predict the same total cloud cover: 100%. From the vertically continuous cloud enclosed by the box between 18 and 19 UTC, it can be seen immediately that as levels further and further apart are considered, maximum overlap becomes an increasingly poor assumption.

In order to quantify this effect, levels were analysed in pairs, with every possible combination of levels being considered, and no 'double-counting'. For each pair, four possible values for the combined cloud cover (C) of the two levels were calculated. The first was the combined cloud cover obtained assuming random overlap, using the standard definition

$$C_{\text{rand}} = c_{\text{a}} + c_{\text{b}} - c_{\text{a}}c_{\text{b}} \tag{1}$$

(where c_{a} and c_{b} are the cloud covers of the lower and upper levels respectively), the second was the value obtained assuming maximum overlap, defined as

$$C_{\text{max}} = \max(c_{\text{a}}, c_{\text{b}}), \tag{2}$$

the third was the value obtained assuming minimum overlap, defined as

$$C_{\text{min}} = \min(1, c_{\text{a}} + c_{\text{b}}), \tag{3}$$

and the fourth was the combined cloud cover that was actually observed, C_{true}. Note that the subscript 'max' corresponds to the maximum *overlap* and not the maximum possible C; in fact C_{max} is the *minimum* possible value of C (see Fig. 1). Pairs in which either of the levels had a cloud cover of zero or unity were rejected, as in these cases all values of C are equal. Hence after averaging over a sufficiently large number of events, the position of the observed $\bar{C}_{\text{true}}$ between $\bar{C}_{\text{max}}$ and $\bar{C}_{\text{rand}}$ (as a function of level separation) will tell us precisely how a radiation scheme ought to weight cloud overlap between the two extremes of maximum and random.

A problem to consider when deriving overlap at 94 GHz is attenuation by liquid water; when heavy rain is present at low levels the radar beam can be completely obscured, resulting in vertical swaths of apparently cloud-free air directly above the rain. This has the effect of increasing the apparent overlap since the erroneously cloud-free regions are stacked on top of each other. We therefore use measurements taken by a drop-counting rain gauge at Chilbolton to reject from the analysis all events for which the rain rate exceeded 0.5 mm hr^{-1} at any time during the sample period. The effect on the derived overlap characteristics was small because less than 10% of the data were removed in this way. The effect of drizzle falling beneath liquid water clouds was investigated by restricting the analysis to regions where the temperature was below 0°C:

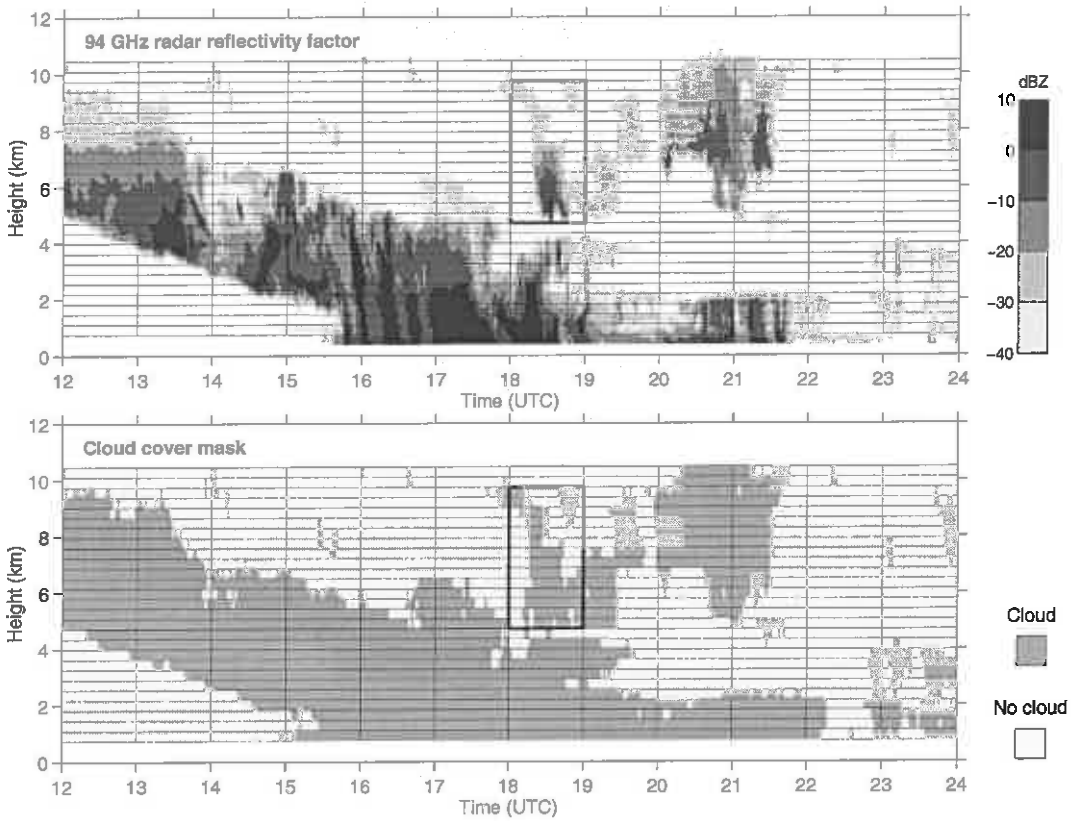

FIG. 2: An example of cloud radar data used to derive the cloud cover mask, from 11 December 1998. Intermittent light drizzle was measured at the ground between 17 and 19 UTC. The resolution of the grid is 360 m and 1 hour.

the change in the overlap statistics was negligible. Another possibility is that large but radiatively-unimportant snow crystals falling beneath ice clouds could be detected by the radar and bias the results. Analysis of simultaneous radar and lidar returns from ice clouds at all heights by Hogan and Illingworth (1999) revealed that this is a rare occurrence; in 94% of their data the radar and lidar cloud base agreed to within 360 m (the highest vertical resolution considered in the present study).

3. Results

The results for boxes measuring 360 m by 1 hour are shown in Fig. 3. Pairs of levels have been grouped together according to their vertical separation, but separated according to whether they are vertically continuous (i.e. the cloud cover in every interstitial level is greater than zero) or non-continuous. We see that in the case of vertically continuous cloud, as the level separation is increased from 360 m to 4 km, $\bar{C}_{\text{true}}$ moves from a value close to that calculated assuming maximum overlap, to essentially the random overlap value. This contrasts with most current GCMs which apply maximum overlap to all vertically continuous levels. In the case of vertically non-continuous cloud on the other hand, there appears to be no significant deviation of $\bar{C}_{\text{true}}$ from that predicted assuming random overlap, in agreement with the schemes used in most GCMs. Of course in individual cases C_{true} takes values anywhere between the extremes of C_{max} and C_{min}.

A simpler and more useful way of presenting these findings is in terms of an 'overlap parameter' α that expresses $\bar{C}_{\text{true}}$ in terms of $\bar{C}_{\text{max}}$ and $\bar{C}_{\text{rand}}$:

$$\bar{C}_{\text{true}} = \alpha \bar{C}_{\text{max}} + (1-\alpha)\bar{C}_{\text{rand}}. \tag{4}$$

Hence $\alpha = 0$ corresponds to random overlap and $\alpha = 1$ to maximum overlap. Figure 4 depicts α as a function of level separation, again for 360 m and 1 hour resolution. The observed values of α would seem to be best fitted by an inverse-exponential of the form

$$\alpha = \exp\left(-\frac{\Delta z}{\Delta z_0}\right), \tag{5}$$

where Δz is the level separation and Δz_0 is an e-folding or 'decorrelation' distance. The value of Δz_0 has been estimated for each of the three temporal resolutions and four vertical resolutions by performing a least-squares fit to the observations, but weighting each observation by the number of events from which the average was calculated. The results are shown in Table 1. Hence if cloud overlap were to be parameterised in models using Eq. 5 then the value of Δz_0 could be chosen to match the model resolution. The weighting is necessary because cloud frequency obviously decreases with increasing physical thickness, and

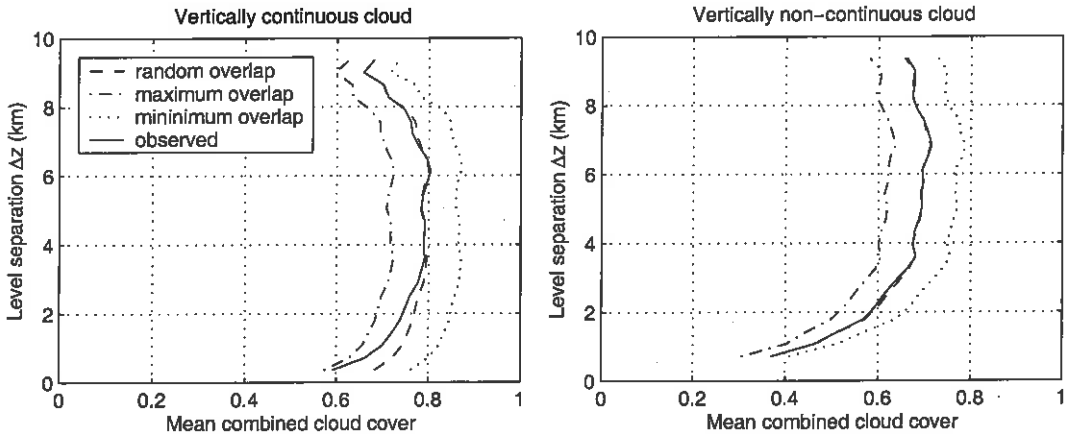

FIG. 3: The mean observed combined cloud cover of pairs of levels as a function of level separation (solid line), together with the values calculated using three different overlap assumptions. The vertical resolution was 360 m and the temporal resolution was 1 hour. Only events where the cloud cover at both levels was greater than zero and less than one were used. The left panel was compiled from events for which every intermediate level contained some cloud and the right panel corresponds to cases for which at least one of the intermediate levels was entirely cloud-free.

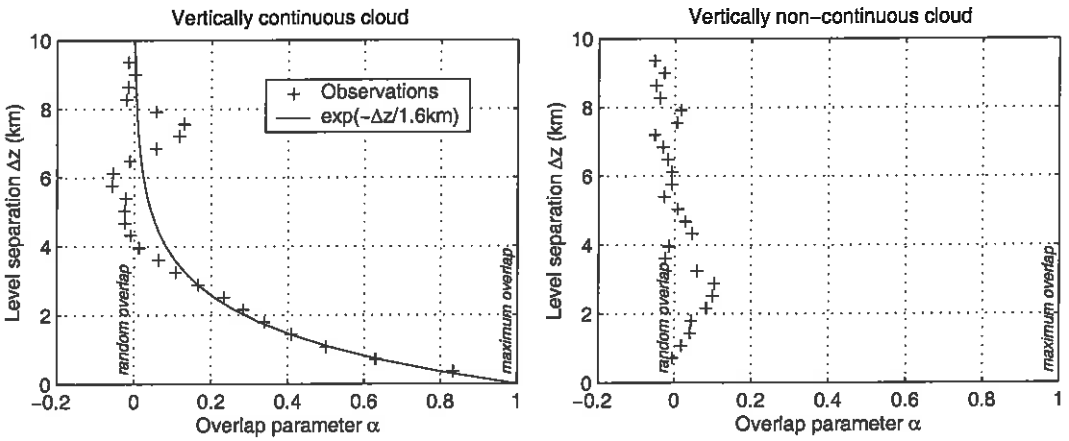

FIG. 4: The overlap parameter α versus level separation for vertically continuous and non-continuous cloud, using boxes 360 m in height and 1 hour in duration. A value of unity indicates maximum overlap and a value of zero indicates random overlap.

Vertical resolution	Temporal resolution		
	20 mins	1 hour	3 hours
360 m	1.40 km	1.60 km	2.04 km
720 m	1.68 km	1.90 km	2.30 km
1080 m	2.04 km	2.15 km	2.48 km
1440 m	2.54 km	2.56 km	2.93 km

TABLE 1: Values of the e-folding distance Δz_0 for different vertical and temporal resolutions.

some possible statistical noise is apparent in α for level separations of more than 7 km. Nonetheless, it is remarkable that as little as a few days of data are sufficient to exhibit essentially the same overlap behaviour as shown in Fig. 4, indicating that this 71 day dataset is easily long enough to derive robust values of Δz_0.

It can be seen from Table 1 that a decrease in either temporal or vertical resolution results in an increase in Δz_0 and thus an increase in the degree of overlap for a given level separation. The change with temporal resolution can be explained by considering an isolated cloud; as the box becomes larger the cloud will occupy a decreasing fraction of the box and the apparent degree of overlap must increase. Indeed, the degree of overlap can never decrease with decreasing temporal resolution. A reduction in vertical resolution can, in individual cases, result in either an increase or a decrease in the degree of overlap, but it simply turns out that the former is more common, particularly for adjacent levels. It is found that Δz_0 does not have a significant dependence on whether the pairs of levels are taken from the upper or lower troposphere. One interesting finding is that with a temporal resolution of 3 hours and a level separation of between 6 and 8 km, α falls to -0.1, indicating a tendency for a lower degree of overlap than even that predicted by the random overlap assumption. The reason for this is that in Southern England during winter, fronts are almost entirely responsible for clouds more than 5 km thick, and these have a char-

acteristic 'slanted' signature in radar time-height sections that can only really be detected in sections of 3 hours or longer (Fig. 2 is a striking example).

4. Conclusions

A simple method for using long-term radar observations to characterise cloud overlap has been developed that expresses mean overlap in a way that could be implemented in GCMs. It has been found that the mean overlap of vertically continuous clouds is distinctly more random than models usually assume, and this will probably have a significant effect on the predictions made with such models. Before applying the findings of this study to global models it would be advisable to use the technique to derive overlap statistics from cloud radars in other locations, and in all seasons, since the overlap characteristics of convective clouds may be appreciably different from those of frontal clouds. A number of 35-GHz cloud radars have recently been deployed at various locations around the globe as part of the Atmospheric Radiation Measurement program (Moran et al. 1998), which would be ideally suited to this task. It would also be a useful application of the proposed spaceborne 94-GHz radar on board 'CloudSat', which is scheduled for launch in spring 2003 as part of the NASA Earth System Science Pathfinder program.

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